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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: April 25, 1978

Project Title: Low Energy Experiment to Measure a Weak Coupling of the Neutrino Current

Project No: B-509 (Sub-project is G-41-668/Ahrens/Physics)

Project Director: Dr. T. P. Lang, Jr.

Green Cd.

Sponsor: National Science Foundation

Agreement Period: From 3/15/78 Until ~~8/31/79~~ 3/31/80
(Grant Period -- Includes flexibility period)

Type Agreement: Grant No. PHY78-01558, dated 4/3/78

Amount: $234,165 B-509
45,385 G-41-668 (NOTE: Total Cost-Sharing required -- $14,737)
$280,000 TOTAL NSF

Reports Required: Final Technical Report; Summary of Completed Project

Sponsor Contact Person (s):

Technical Matters

Douglas Bryman
Program Officer
Nuclear Physics Program
National Science Foundation
Washington, D. C. 20550
202/632-4317

Contractual Matters
(thru OCA)

Ms. Mary Frances O'Connell
Grants Manager
MPE/BBS/SE Branch
Division of Grants and Contracts
National Science Foundation
Washington, DC 20550
202/632-2858

NOTE: Continuation of B-484

Defense Priority Rating: N/A

Assigned to: Applied Sciences Laboratory (ASL/APB) (School/Laboratory)

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CA-3 (3/76)

B-171 2

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 5/11/81

Project Title: Low Energy Experiment to Measure a Weak Coupling of the Neutrino Current

Project No: B-509 (subproject is G-41-668/Ahrens)

Project Director: Dr. T. P. Lang, Jr.

Sponsor: NSF

Effective Termination Date: 8/31/80

Clearance of Accounting Charges: 8/31/80

Grant/Contract Closeout Actions Remaining:

- _ Final Invoice and Closing Documents
- x Final Fiscal Report (FCTR)
- x Final Report of Inventions (if positive)
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ______________________

Assigned to: EML/PSD (School/Laboratory)

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CA-4 (1/79)

B-509

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

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PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address Georgia Institute of Technology Atlanta, Georgia 30332	2. NSF Program Nuclear Physics	3. NSF Award Number PHY78-01558
	4. Award Period From 4/15/78 To 8/31/80	5. Cumulative Award Amount $480,000.00

6. Project Title
Low Energy Experiment to Measure a Weak Coupling of the Neutrino Current

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

A measurement of the cross section for the interaction of neutrinos with deuterons using reactor-produced antineutrinos determines a basic parameter of the weak interaction, namely, the isovector axialvector coupling constant of the weak neutral current. This project continued the Georgia Tech neutrino program establishing feasibility for measurement of this cross section.

The measurement requires an array of particle detectors contained within a massive shield in close proximity to a nuclear reactor. A shield, containing some 30 tons of lead and other materials, was constructed at a site which is 15.5 meters from the center of the core of a reactor at the Savannah River Plant, Aiken, S.C. A complex system of cosmic ray detectors was mounted on the exterior of the shield to permit the electronic rejection of spurious events caused by cosmic rays. The effects of these measures upon the radiation environment within the shielded volume were investigated by a variety of detectors, including prototypes of particle detectors for the cross section measurement.

The non-antineutrino radiations within the shield are sources of background which interfere with the cross section measurement. The feasibility of the measurement depends upon reducing this background to acceptable levels.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses			2		
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results			X		
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
T.P. Lang		4/30/81

From Sept. 79 Proposal

Of further basic importance is the use at low energy of electron neutrinos, s opposed to muon neutrinos at high energy.

. ıother good feature of the experimental setup, if not directly related to the basics of the theory, still connected to the straightforwardness of theoretical interpretation, is the separation of target (and proton detection) volume from neutron detection volume. Aside from permitting effective discrimination against background, this provides a handle on the potential problem of neutron leakage.

It should be mentioned that the deuteron disintegration in the charge exchange mode, $\bar{\nu}_e + d \rightarrow 2n + e^+$, can also be thoroughly investigated with the present setup, thus permitting an exacting check on equipment working order and a direct comparison with the neutral process.

Other workers have established an experimental upper limit of 26.4 x 10^{-45} cm^2 for the cross section for this reaction, and their work is continuing.[5] These experiments depend upon detection of the product neutron alone as the event signature, in contrast to the presently proposed experiment which shall detect both product nucleons. Dependence upon the abbreviated signature requires extreme care to avoid false signatures from a variety of neutron sources which include the adjacent reactor.

Down the line, after establishment of G_{Av} for the electron neutrinos, it is planned to go after G_{As} either by another disintegration process or by nuclear excitation. Processes depending on both coupling constants need then no longer be excluded. (Perhaps it should be mentioned here that several in vogue gauge theories exclude the presence of a weakly interacting isoscalar axial-vector current.)

3. SUMMARY OF SCIENTIFIC PROGRESS

T.P. Lang, Project Director, says this section was accepted as the Annual Report

Shield and CRUMB

The graded bulk shield and cosmic ray umbrella anticoincidence detectors (CRUMB) which have been constructed at the reactor experimental site at the Savannah River Plant are shown schematically in Figure 4. The minimum of ten inches of lead surrounding the central shielded volume provides shielding from the environmental radiation within the room and some protection from cosmic rays. The two imbedded two-inch thick shells of borated polyethylene serve to thermalize and capture neutrons within the shield. The cross-section of the experimental area within the shield is 17 inches by 17 inches. It is 68 inches long. The total weight of the shield is 35 tons. Photographs of the apparatus are displayed in Figures 1 and 2.

The CRUMB system is made up of nine liquid and five plastic scintillator cells. The top and sides have a minimum thickness of four inches and the ends one and one-half inches. A total of 44 photomultiplier tubes view the 1500 liters of scintillator.

The layer of borated polyethylene below the bulk shield and the CRUMB detectors serve as an outer passive neutron shield, but the CRUMB serves primarily as an active cosmic ray veto system. It produces a veto pulse whenever a cosmic ray interacts within its detectors. The time width of the veto pulse has been shown to be extremely important in reducing the background signature rate in our prototype modules. A width of 500 microseconds is expected to be necessary to achieve minimum background rates.

The efficacy of the shield and CRUMB has been extensively investigated at Georgia Tech. A NaI detector survey of the radiation inside the shielding was used to calculate the photodisintegration rate of deuterons in the target scintillator. (Figure 5 contains some NaI spectra.) It is calculated from measured gamma spectra that the photodisintegrations will contribute 258/day to the background rate in the cosmic ray flux at Georgia Tech.

Studies of the shield at the reactor have begun. It is already apparent that the cosmic ray flux is reduced at the new site. The CRUMB rates are about one-half their rate at Georgia Tech. This reduction arises from the considerably increased overburden at the reactor. It is an expected but quite welcome result, given the data obtained at Georgia Tech which demonstrate that the cosmic rays provide most of the background events.

Further studies at the reactor are in progress.

Dual Concentric Module

Details of the experimental module are shown schematically in Figure 6. The inner detector, displayed individually at the top of the figure, is an acrylic cylinder. Its central active volume of six liters contains the liquid scintillator that provides the target deuterons and detects the proton pulse. This volume is viewed by fast, low noise five-inch photomultiplier tubes through six-inch light pipes which are filled with pure non-scintillating octane.

The outer detector is displayed schematically as the second object from the top in Figure 6. The sensitive volume of this detector is the central 32-inch long cylindrical annulus, which contains the ^{6}Li-loaded scintillator which detects the neutron. This volume is viewed by a total of 16 three-inch diameter photomultiplier tubes through seven inch long light pipes. This design for the outer detector capitalizes upon our serendipitious discovery that acrylics alone do not degrade the ^{6}Li scintillator. The entire cell is constructed so that only acrylic or teflon coated stainless steel seal rings contact the scintillator. Seal compression and mechanical rigidity are provided by stainless steel bolt circles. An examination of the light collection properties of the cell suggested that an array of three-inch diameter photomultiplier tubes would be more efficient than the one nine-inch photomultiplier tube on each end of previous outer detector prototypes.

To form an experimental module, the inner detector is placed inside the outer detector, as shown in the cut away drawing of Figure 6. A photograph of the detectors also is displayed in Figure 6.

Extensive tests have been performed with these detectors, separately and combined as a prototype module. The inner detector must detect a considerable fraction of the protons released by the disintegration of the deuteron. The energies of the protons extend to extremely low energies. Our mastery of the interpretation of very low energy events in the inner detector includes extensive computer modeling of the response of the detector to low energy gamma rays and a measurement of the intrinsic response of the inner detector liquid scintillator to protons. This last effort was conducted at the Oak Ridge Electron Linear Accelerator (ORELA), where a time-of-flight neutron beam produced knock-on protons in the scintillator.[6] The results of this study are presented in Figure 7. Response tests of the outer detector scintillator to neutrons have been made; Figure 8 demonstrates the response of this scintillator to neutrons.

A prototype module was used to investigate the background signature rate in the laboratory at Georgia Tech. Placed inside the massive shield and cosmic ray anticoincidence system, the module produced 269 background events per day, the vast majority of which were shown to be cosmic ray related. Improvements in the cosmic ray anticoincidence system which have already been installed at the reactor experimental site are expected to reduce this rate to 46/day or 276/day for six modules. These rates do not include the effects of the observed reduction in the cosmic ray flux at the SRP experiment site.

Data Acquisition System

A minicomputer based data acquisition and control system has been obtained to record the maximum information during the data collection interval. Inasmuch as possible, electronic "thresholds" will be set as low as practical, and energy windows set as wide as practical, so that in the later data analysis the events may be examined with thresholds and windows set by alternate analysis criteria, rather than having to repeat the data collection for multiple threshold and window settings. This approach is practical with the data collection system planned.

The hodoscopic data collection and analysis system has been designed to record, for each event fitting minimum criteria in each of the concentric detector modules, the following (as screened by the anticoincidence-event signature logic):

1. The pulse height in the target/proton detector region,

2. The pulse height in the neutron detector within the delayed coincidence window,

3. The time between events in the two regions,

4. Hodoscopic correlation data concerning events occurring in a coincidence window in other detector modules, and

5. Time, date and event number.

These raw data will be saved "as is", for later detailed sorting and analysis. Summary information can be generated for on-line experiment analysis, monitoring, calibration and control.

The system is based on a 32-K word Digital Equipment Corporation PDP-8A 620 computer with RK05 removable disks and dual DecTape. A major portion of the computer hardware was obtained through Georgia Tech Research Improvement grants. Direct computer interface to CAMAC Crate is provided. A 12-Channel Scaler and digital input-output registers provide for singles and event input via the CAMAC bus. Two CAMAC Waveform analyzers clocked in parallel provide a mechanism for obtaining the pulse-heights of signals in both inner and outer detectors during a possible event of interest. These fast (about 50 nanosecond) Analog-to-Digital converters with memory continuously sample and store on a circular buffer, at selectable time intervals, the signals from the detectors. The sampling is stopped by a post-trigger derived from fast-logic detection of a "suitable" event. Conventional pulse height analysis is provided by Nuclear ADC's interfaced directly to the computer. The interface provides control of the ADC's and their associated live-time clocks and two modes of readout. It was designed to be expandable for multiple ADC's or similar devices. It has been built and tested initially for two ADC's.

Software has been written to access the data collection buffers from a high-level interactive language for data manipulation, analysis, storage and display. The software also provides for readout and control of the CAMAC modules via a generalized function, FCAM(F,N,A,DATA), where F,N,A and DATA have the usual CAMAC definitions.

If the waveform analyzers perform as anticipated, then an additional interface will be built to provide direct readout with zero suppression to reduce the time currently required for readout (about 15 milliseconds). Since most of the data stored will be zeros in the actual experiment, this buffer could be hardware scanned and only the address (time) and data (pulse-height) for non-zero data be stored. The ADC controller will also be expanded to accommodate a third nuclear ADC.

Currently the software provides for general access to the data collection system. It is intended to develop a foreground-background system with the experiment being the foreground task, with summary analysis, etc. being background interactive tasks. To this end, experiment specific code will be converted to machine language interrupt driven tasks to reduce deadtime.

Cross Section Calculations

Calculations have been performed on the cross sections

$d\sigma(q)/dE$, $\int dq\phi(q)\,d\sigma(q)/dE$ and $\int_{E_t} dE \int dq\phi(q)\,d\sigma(q)/dE$

for the antineutrino disintegration of the deuteron in the neutral mode. E is the energy of the exiting proton, t stands for threshold, q is the incident antineutrino energy and $\phi(q)$ the equilibrium fission antineutrino spectrum. In contrast to previous calculations, the phase space factor occurring in $d\sigma/dE$ has been evaluated rigorously necessitating a numerical triple integration. This leads to reliable proton spectra and integral cross sections. The reason for the previously found considerable insensitivity of the cross section to the "range correction" has been quantitatively established. The major obstacle to more accurate (better than 10%) calculated cross sections for comparison with experiment is now the equilibrium fission spectrum. Once the proposed measurement of this spectrum is completed, calculations, particularly those involving the deuteron D-state and weak magnetism, become of interest, and evaluations become important of reactions allowing the determination of other neutral current coupling constants. Aside from the customary vector coupling, the question of an isoscalar axial vector coupling is particularly interesting.

Neutrino Spectra Calculations

Two approaches were taken in recent calculations of the neutrino spectrum from fission products. The first improved upon the previously reported results by capitalizing upon the more recently compiled fission yields, empirical mass defects and decay scheme data. Spectra for the decays of fission products of ^{238}U and ^{239}Pu were calculated as well as for those of ^{235}U. Since the fission of all these nuclides will contribute to the neutrino spectrum at the reactor, a desire for precision demanded knowledge of their effects, although the effect of fission produced decays of ^{238}U and ^{239}Pu is known to be small. These spectra were published at the 1978 International Neutrino Conference.[7]

The most recent effort was based upon a novel method of extending available spectroscopic knowledge into the unknown region. This method bases the extrapolation upon the spectroscopy of even versus odd nuclides of the same Z, rather than depending upon the even-odd A, even-odd Z discrimination of previous calculations. The data and method upon which the calculation of this spectrum was based permit the reproduction of available fission produced beta decay spectra. This spectrum is the one from which one derives the inverse beta decay positron spectrum discussed elsewhere in this proposal. Publication of these results is expected in the near future.

Monte Carlo Calculations of Neutron Detection Efficiencies

The Monte Carlo calculations of the neutron response of the detector module have been revised to reflect the actual composition of the different detector regions and the exact geometrical shapes of the various regions of the module, including cell fabrication materials and air spaces.

The original calculations, on which the detector design was based, were made using the Monte Carlo Code O5R, from the Oak Ridge National Laboratory. A revised version was created to run on the new Control Data CYBER-74 system, which replaced the U-1108 at the Georgia Tech central computer facility. Extensive work has been completed in verifying the original calculations. The revised version contains a new analysis scheme of the Monte Carlo history data which permits direct calculation of the fraction of neutrons captured in each individual element in both inner and outer detector regions. This permits evaluation of the earlier approximations used and a direct evaluation of the neutron energy, space, time and element capture parameters. Calculations have been made to evaluate the effects of walls, voids, light pipes and actual detector dimensions.

Preliminary Feasibility Results for Deuteron Disintegration Experiment

The technical approach, including the development and manufacture of special liquid scintillators, is the result of many years of experimental investigations. The detectable products of the antineutrino disintegration of a deuteron are a proton and a neutron. By detecting both of these product particles and the application of energy and timing restrictions, the event signature can be made quite unique. The experiment will consist of six identical modules. Each module will contain two coaxial cylindrical scintillation detectors, shown in detail in Figure 6.

The central, 95% deuterated, scintillator serves both as the target material and as the detector for the proton. The neutron migrates to the outer detector which contains ^{6}Li. Upon absorption of a neutron, the ^{6}Li disintegrates into a triton and an alpha particle, with a minimum total kinetic energy of 4.8 MeV. Temporal and spatial distribution functions obtained by multi-group Monte Carlo neutron transport calculations were used to determine the timing requirements for the event signature and the dimensional requirements for detector size.

Given a knowledge of the antineutrino spectral flux from fission product decays at the experimental site and the variation of the deuteron disintegration cross section with energy, the kinetic energy distributions for breakup nucleons were calculated (see Appendix B). Knowledge of these energies allows restriction of the energy range of interest in the proton detector. Distributions for the time spent by the neutron between creation and absorption by ^{6}Li, about 90 percent being captured within 33 microseconds, were obtained from Monte Carlo neutron transport calculations. The ^{6}Li disintegration occurs with a relatively delimited energy. The signature for the observation of an antineutrino disintegration event is a pulse in the proton detector corresponding to an energy that the proton is likely to possess, followed within 33 microseconds by a ^{6}Li breakup in the outer detector.

The event rate to be determined from the experiment has the predicted value of 2.0 hour^{-1}.

$$I_o = \phi_{\bar{\nu}} \, \sigma_{\bar{\nu}d} \, N = 2.0 \text{ hour}^{-1} = 49.2 \text{ day}^{-1} ,$$

where:

$$\phi_{\bar{\nu}} = 3 \times 10^{13}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ ,$$

$$\sigma_{\bar{\nu}d} = 7.3 \times 10^{-45}\ \mathrm{cm}^2\ ,$$

and $\quad N = 2.6 \times 10^{27}$ deuterons/40 liters.

The actual detected rate, S, due to this reaction will be smaller by a factor determined by the experimental efficiency and the number of reaction products falling within the signature limits.

$$S = k_p\ k_n\ k_t\ I_o = 0.97\ \mathrm{hour}^{-1} = 23.1\ \mathrm{day}^{-1}\ ,$$

where the fractions k_p, k_n and k_t are the fractions of the total number of ν_e events which fall within the signature constraints E_p, E_n and T_t. The values are:

$$k_p = 0.58 \qquad k_n = 0.90 \qquad k_t = 0.90.$$

The uniqueness of the signature devised for antineutrino disintegration of the deuteron event would allow a measurement to any desired precision given sufficient time. The constraints imposed by long term instrumentation instability and the resources of the experimenters require that the time to produce the desired result be reasonable. Consequently, a feasibility study should emphasize those parameters which affect the counting time.

The counting time can be shown to have the form

$$T = 4B/k^2S^2\ ,$$

where B is the background rate and k is the constant specifying the relative statistical accuracy of the measurement, $k = \sigma_s/S$, where σ_s is the uncertainty in the signal S. From this expression, it is apparent that lowering the background signature rate is the appropriate strategy for reducing T for a given S.

The sources of B are discussed in Appendix A, where it is shown that cosmic rays contribute the majority of background events. A careful analysis of those data permitted an estimate of the reduction in B available from the present extended CRUMB coverage and from the use of an updating anticoincidence in the CRUMB electronics. The value of B at Georgia Tech was found to be 1872 day^{-1} for six modules (but based on measurements on only one module) without the effect of the improvements and is predicted to be 534 day^{-1} with the improvements.[8]

It should be noted here that the expected reduction in B is accomplished by simple hardware additions to the experimental arrangement and that these additions have been implemented at the reactor site. The experimental effort will soon permit a determination of their actual effect. It is also worthy of mention that these reductions do not include the effects of the reduction of the cosmic ray flux from the increased overburden at the experimental site.

From the above values of B, one can calculate the counting time T required for given values of k. A set of such values is given in the following table. It is apparent that good statistical precision is available within reasonable counting times.

TABLE OF ESTIMATED COUNTING TIMES

Background Rate, B	Statistical Precision of Measurement, k 0.25	0.20	0.10
1872/day	225 days	351 days	1403 days
534/day	64 days	100 days	400 days

The counting times do not include the instrumental dead time. The measured dead time of the apparatus due to the cosmic ray anticoincidence shield, at the Georgia Tech site which has no significant mass above, would imply approximately 50% for full shield coverage. However, this dead time is significantly reduced by a large amount of massive building material above the SRP reactor site.

There is good justification for viewing these computed values of the counting times as an upper limit to that which will actually be achieved. Several important effects were not included in the data and each can only reduce the value of T. These effects are:

1. Application of prompt rejection for module-to-module scattering. At present the only prompt rejection is that between detectors in a single module.

2. Incorporation of the planned data collection and analysis instrumentation will allow exact optimization of the values for the event signature delimeters. This has not been possible with the previous instrumentation.

3. Greatly increased overburden at the SRP site compared to the negligible amount at the site of previous measurements. This already observed effect was not included in our estimates of the reduction of B.

It is not unusual for neutrino experiments to consume many months or even years of counting time. The fundamental limitation on the length of counting time is the requirement of maintaining apparatus and instrumentation calibration so that accumulated data may be legitimately integrated. Very careful and detailed consideration has gone into the development of instrumentation and procedures for calibrating and monitoring performance. All of these produce a "coherence" time certainly measured in years. Thus not only is the experiment feasible, but a high degree of statistical accuracy is possible.